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Suppression of Steady State Error Using Sliding Mode Control For Dc-Dc Buck Converter

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(Abstract) The steady state error in DC-DC Buck converter is generally suppressed by using hysteresis modulation based sliding mode controller. By introducing additional integral term of the state variables to hysteresis modulation to control steady state error can be reduced further. Moreover, the error increases as the converter switching frequency decreases. In this paper, specifically it is proposed that an addition of one more integral term of the controlled variables is incorporated for constructing the sliding surface of the indirect sliding mode controllers. The two different integral methods have been implemented to reduce the steady state error in DC-DC Buck converter. MATLAB/Simulink is used for testing the results.

Keywords: Additional Integral Sliding Mode; Buck Converter; Pulse Width Modulation; Integral Sliding Mode; Sliding Mode Control.

1. Introduction

The sliding mode control is a non linear system, it is derived from variable structure system. It is well known for their stability and robustness against parameters, line and load variation. The flexibility is the design choice. Implementing of SM controller is relatively easy when compare with the other controllers. Practical adaptation of SM controller in DC/DC converters is often limited by two major concerns, the non constant operating frequency of SM controller and the presence of steady state error in the regulation. To consider the first concern, some possible methods of fixating the switching frequency of SM controllers have been proposed. Mainly these include the use of adaptive strategies, the incorporation of the constant timing function or circuitries and the indirect implementation of the SM controllers. To consider the second concern, it has been widely known that the steady state errors of SM controlled system can be effectively reduced through the use of an additional integral term of the state variables in the SM controllers. The use of additional integral state variables for constructing the sliding surface of indirect SM controllers for DC-DC converters to reduce the steady state errors.

2. Hysteresis Modulation based Sliding Modecontroller

A common form of the SM controllers for nth order converter adopts a switching function

$$U = \begin{cases} u+ & \text{when } S>k \\ u- & \text{when } S<-k \end{cases} \quad (1)$$

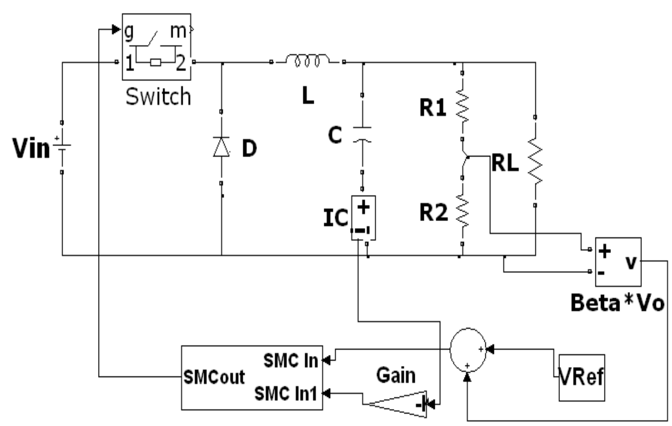

Figure 1: Schematic diagram of Buck Converter

Where k is a parameter controlling the switching frequency of the system, and S is the instantaneous state variable's trajectory of reduced order which is expressed as

$$S = \sum_{i=1}^{n-1} \alpha_i x_i \quad (2)$$

Where α_i for i=1 to n-1 denotes the sets of the control parameters i.e. sliding coefficient. When k=0, the converter operates ideally at an infinite switching frequency with no steady state error, this is not true in practice. In case of HM based SM controllers, the steady state error increases as their switching frequency decreases. To obtain a better result to reduce the errors is to introduce an additional integral term of the state variables to the SM controllers is introduced which transform it into an ISM controller. ISM controllers can be obtained by

$$S=\sum_{i=1}^{n-1}\alpha_i x_i+\alpha_n\int\sum_{i=1}^{n-1}x_i dt \qquad (3)$$

2.1 Indirect Sliding Mode Controllers

Indirect form of any SM controllers can be implemented within change their control law. Assume some condition, During SM operations S=0.From such an assumption, an equivalent control signal Ueq can be derived in terms of respective state variables, to derive the equivalent control the time differentiation of equation (3) is first derived that is

$$\dot{S}=\sum_{i=1}^{n-1}\alpha_i\dot{x}_i+\alpha_n\sum_{i=1}^{n-1}x_i \qquad (4)$$

Equating S=0 and solving for equation gives general form

$$U_{eq}=\mathrm{G}\left(\dot{x}_1,\dot{x}_2,\ldots..,\dot{x}_{n-1},x_1,x_2\ldots.x_{n-1}\right) \qquad (5)$$

Where 0 < Ueq < 1 is a function of a state variables $\dot{x}_i$ and x_i for i=1,2….,n-1.In practice in the case of PWM based SM controller implementation, the control signal Ueq is constructed through a pulse width modulator using a constant frequency ramp signal Vramp and a feedback control signal V_c. Hence both Vramp and V_c are functions of state variables $\dot{x}_i$,and x_i , it is important point that the indirect construction of $\dot{S}$ using indirect approach uses state variables of one time derivative order lower than the original HM based ISM controller.

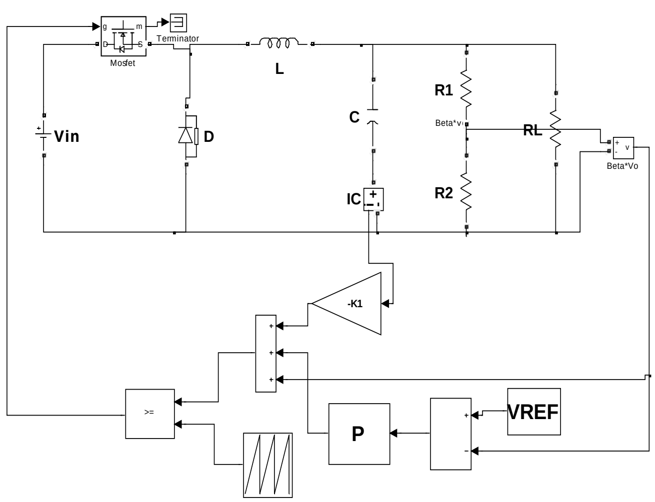

Figure 2: Simulink model PWM based integral sliding mode controller.

2.2 Steady State Error in Indirect Integral Sliding Mode Controllers

First in the case of the direct ISM controller, the sliding surface constructed comprises the integral elements of the steady state errors i.e., $\int x_i dt$ for i=1, 2,…..,n-1. Recall that $\int x_i dt$ is a component that directly accumulates the existing steady state errors. Hence when the state variables trajectory S is directed to track the sliding surface to a point of equilibrium, the steady state errors are automatically reduced

For the indirect ISM controllers , the variable $\int x_i$ dt are not explicitly reflected in the control signal these integral function are embedded in the sliding surface , of which required error correction are indirectly computed using the state variables x_i.Since there is no direct integral signal $\int x_i$ dt that corrects the error of the state variables, the capability of the corrections is then dependent on the accuracy of the indirect integral computation, steady state errors present in the computation, naturally this problem will be further increased if the switching frequency is decreased.

3. Proposed Solution For Buck Converter

An additional integral term of the state variables i.e., $\int[\int x_i\, dt]$ dt for i=1, 2 ….n-1 is therefore introduced to correct the error of the indirect integral computation in the indirect ISM controllers. By adding an integral closed loop to alleviate the steady state error of the indirect integral computation, the steady state errors of the controlled state variables are indirectly alleviated. This is the so called additional integral sliding mode controller proposed in this paper.

In general direct HM (Hysteresis Modulation) form, the proposed AISM controller takes the switching function (1) where

$$S=\sum_{i=1}^{n-1}\alpha_i x_i+\alpha_n\int\sum_{i=1}^{n-1}x_i dt+\alpha_{n+}\iint\sum_{i=1}^{n-1}x_i dt dt \qquad (6)$$

Its time differentiation

$$\dot{S}=\sum_{i=1}^{n-1}\alpha_i\dot{x}_i+\alpha_n\sum_{i=1}^{n-1}x_i+\alpha_{n+}\int\sum_{i=1}^{n-1}x_i dt \qquad (7)$$

The proposed AISM (Additional integral sliding mode) configuration easily resolves the problem of steady state errors in indirect ISM controlled converters.

3.1. Additional–integral sliding mode controller

The proposed AISM controller applied for buck converter using the switching function u= (1/2) (1+sign(S)) and sliding surface gives

$$S=\alpha_1x_1+\alpha_2x_2+\alpha_3x_3+\alpha_4x_4$$

(8) Where u represents the logic state of power switch and α_1 α_2 α_3 and α_4 represents the desired sliding coefficients. Also, in both examples, C, L and r_L denote the capacitance, inductance and instantaneous load resistance respectively. V_{ref}, V_i and V_0 denote the reference, instantaneous input and instantaneous output voltages respectively. β denotes the feedback ratio, i_{ref}, iL, i_c and i_o denotes the instantaneous reference, instantaneous inductor, instantaneous capacitor and instantaneous output currents respectively and ū =1-u is the inverse logic of u. The AISM voltage controlled buck converter, the controlled state variables are the voltage error. x_1 the voltage error dynamics (or the rate of change of voltage error) x_2, the integral voltage error x_3 and the additional integral error x_4 are expressed as

$$x_1=V_{ref}-\beta V_0$$
$$x_2=\dot{x}_1$$
$$x_3=\int x_i\, dt$$
$$x_4=\int[\int x_i\, dt]\, dt \qquad (9)$$

Substitution of the buck converters behavioral models under continuous conduction mode (CCM) of operation into the

time differentiation of (9) gives the dynamics model of the proposed system as

$$\begin{aligned} \dot{x}_1 &= d(Vref - \beta Vo)/dt = -\beta ic / C \\ \dot{x}_2 &= \beta ic / (r_L C^2) - (\beta Vi / LC)u + \beta Vo / LC \\ \dot{x}_3 &= Verf - \beta Vo \\ \dot{x}_4 &= \int (Vref - \beta Vo) dt \end{aligned} \quad (10)$$

The equivalent control signal of the proposed AISM voltage controller when applied to the buck converter is obtained by solving

$$\frac{ds}{dt} = \alpha_1 \dot{x}_1 + \alpha_2 \dot{x}_2 + \alpha_3 \dot{x}_3 ?=$$

Which gives ,u=u_{eq}

$$\begin{aligned} Ueq = {} & \beta L \;/\; \beta v_i \left(1/\; r_L C \;-\; \alpha_1 /\; \alpha_2\right) i_c \\ & + \beta V_0 / \beta v_i + \alpha_3 / \alpha_2 (LC / \beta V_i)(Verf - \beta V_0) \\ & + (\alpha_4 /\; \alpha_2) LC /\; \beta v_i \int \left(V_{ref} - \beta V_0 \right) dt \end{aligned} \quad (11)$$

where u_{eq} is continuous and bounded by 0 and 1 ie $0 < u_q < 1$.

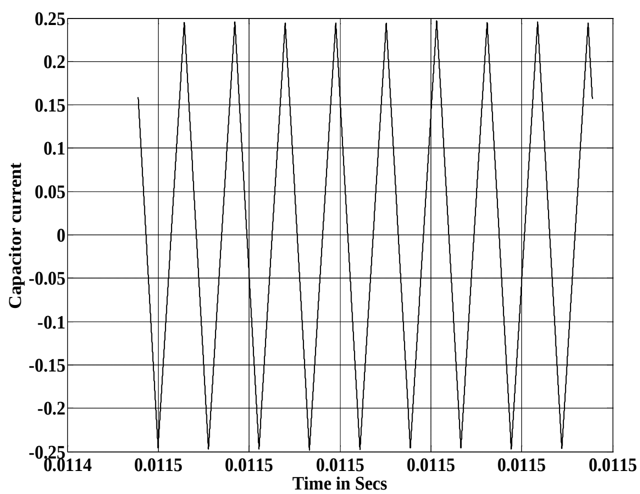

Figure3: Steady state waveform of the state variable capacitor current of the Buck converter.

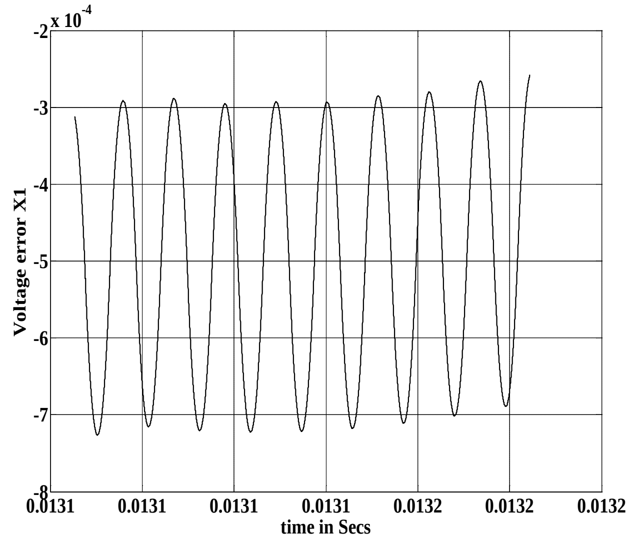

Figure4: Steady state waveform of the state variable voltage error X1 of the Buck converter.

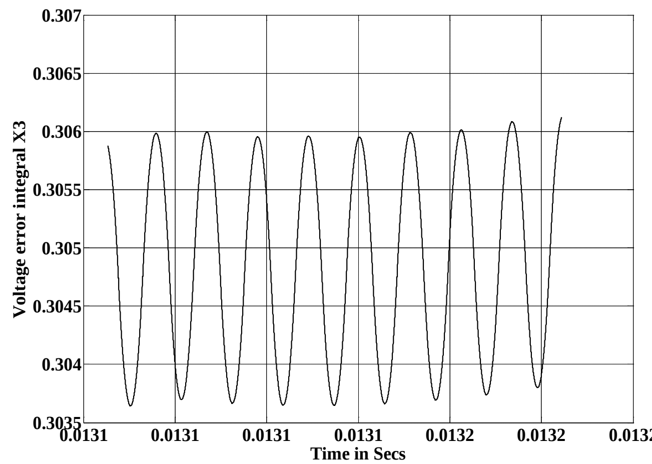

Figure5: Steady state waveform of the state variable integral of voltage error X4 of the Buck converter.

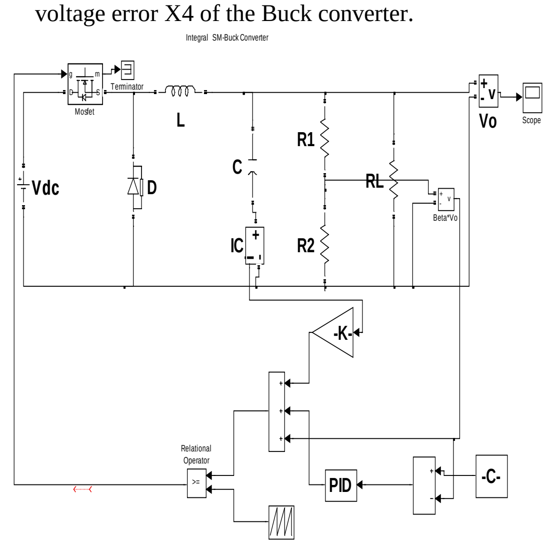

Figure 6: Simulink diagram of the derived PWM based AISM voltage controller for the buck converters

3.2 Indirect Sm Controller in Pwm Form

In PWM form, the proposed AISM voltage controller for the converter is the following expression

$$V_c = -K_1 i_c + K_2(V_{ref} - \beta V_0) + K_3 \int (V_{ref} - \beta V_0)\,dt + \beta V_0$$

$$V_{ramp} = \beta v_i$$

For implementation of indirect SM controller in PWM form, a set of equation comprising a control signal V_C and a ramp signal V_{ramp} with peak magnitude i_{ramp} must be derived using the indirect SM control technique.

Where

$K_1 = \beta L(\alpha_1 / \alpha_2 - 1/r_L C)$; $K_2 = \alpha_3 / \alpha_2 LC$; $K3 = \alpha_4 / \alpha_2 LC$ (12)

are the fixed gain parameters in the proposed controller.

$$V_c = -K_1 i_c + K_2(V_{ref} - \beta V_0) + K_3 \int (V_{ref} - \beta V_0)\,dt + \beta V_0$$

Table 1. Shows for Specification of buck converter

Description	Parameter	Nominal value
Input voltage	Vi	24Volts
Capacitance	C	220µF
Inductance	L	69 µH
Switching Frequency	f_s	200Khz
Minimum load resistance	$_{rL}$(min)	4 Ohm
Maximum load resistance	$_{rL}$(max)	10 Ohm
Desired Output voltage	Vod	12V

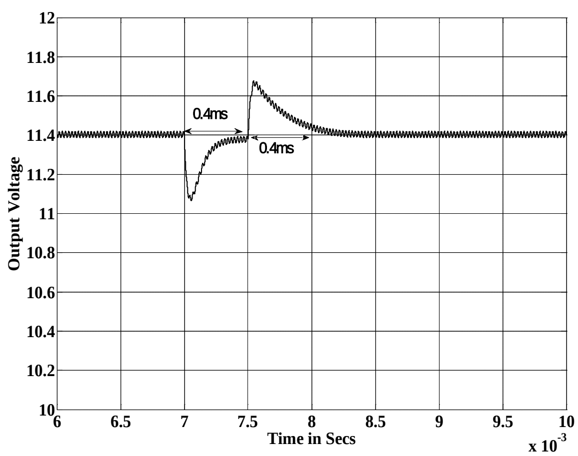

Figure 7: Output voltage waveforms of the PWM based integral sliding mode Buck converter operating at step load changes between 2.5 Ohms and 4 Ohm .

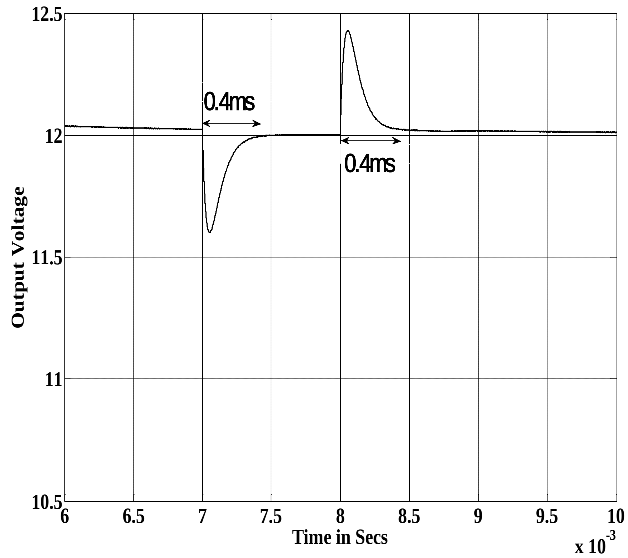

Figure 8: Output voltage waveforms of the PWM based additional sliding mode Buck converter operating at step load changes between 2.5 Ohms and 4 Ohm .

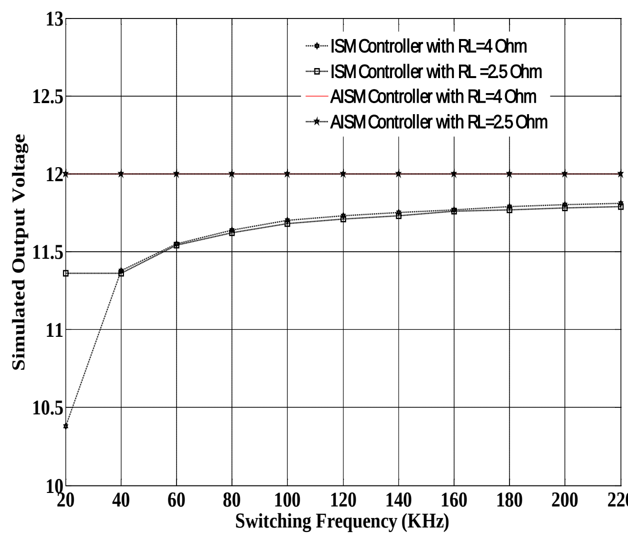

Figure 9: plot of steady state output voltage Vo against switching frequency (fs) of the Buck converter operating under PWM based ISM and AISM controllers at a maximum load resistance of 4 Ohms & a minimum resistance of 2.5 Ohm.

4. Simulation Results

In this paper PWM based ISM controller and AISM controller are designed to give a critically damped response with a bandwidth of 3 KHz.Figure7 shows ISM controller step load change from 2.5 Ω at 7ms and 10 Ω at 8ms with settling time of 0.4ms for both step up and step down load change. It is observed that more ripple in the output voltage waveform.

Figure8 shows AISM controller step load change from 2.5 Ω at 7ms and 10 Ω at 8ms with settling time 0.4ms for both step up and step down load change with very less ripple content compare to ISM controller.

Figure 9 shows the output voltage waveforms for R_L = 10Ω and R_L = 2.5 Ω, of AISM and ISM controller. It is observed that ISM controller shows more steady state error compared AISM controller at low switching frequencies.

5. Conclusion

In this paper both PWM based ISM and AISM controllers are simulated. It is found that the problem of method of the steady state error correction. It's observed that integral sliding mode controller is failing to achieve complete removal of steady state error in both load and line variation. In these controllers the magnitude of the output voltage regulation error increases switching frequency reduces. The inclusion of the additional term is to correct the error of the indirect integral computation. By doing so regulation error of the converter is indirectly alleviated. In the view of this point the AISM is proposed for constructing the sliding surface of indirect SM controllers. It is found that AISM controller is capable of achieving a perfect voltage regulation at low and high switching frequencies.

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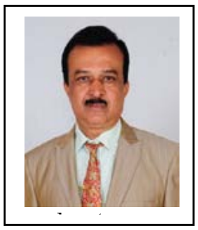

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